Non-obstructing 3D depth cues influence reach-to-grasp kinematics.

Abbreviated Title: depth cues and prehension

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Abstract

It has been demonstrated that both visual feedback and the presence of certain types of non-target objects in the workspace can affect kinematic measures and the trajectory path of the moving hand during reach-to-grasp movements. Yet no study to date has examined the possible effect of providing non-obstructing three-dimensional (3D) depth cues within the workspace and with consistent retinal inputs and whether or not these alter manual prehension movements. Participants performed a series of reach-to-grasp movements in both open- (without visual feedback) and closed-loop (with visual feedback) conditions in the presence of one of three possible 3D depth cues. Here it is reported that preventing on-line visual feedback (or not) and the presence of a particular depth cue had a profound effect on kinematic measures for both the reaching and grasping components of manual prehension – and despite the fact that the 3D depth cues did not act as a physical obstruction at any point. The depth cues modulated the trajectory of the reaching hand when the target block was located on the left side of the workspace but not on the right. These results are discussed in relation to previous reports and implications for brain-computer interface decoding algorithms are provided.

200 words.

Introduction

To perform the everyday task of reaching to pick up a glass of drinking water, it is necessary for the brain to carry out numerous computations and within a very short period of time (~100 ms; Knill, 2005). To provide but one everyday example, once a glass of water has been identified as the target object, the brain must generate accurate motor commands for the reaching limb via an integration of various visual cues about both the environment and the specific three-dimensional (3D) profile of the glass (Knill, 2005). Only once these calculations have been processed, is it then possible to reach and grasp the glass effectively. Not surprisingly, it has been reported that visual input(s) can significantly affect the ability to accomplish goal-directed reaching and grasping, also known as manual prehension (for example, Connolly & Goodale, 1999; Saunders & Knill, 2004; Whitwell, Lambert & Goodale, 2008).

During the 1980s, Jeannerod (1981, 1984) demonstrated that manual prehension can be divided into two distinct neural and behavioural components - reaching and grasping. Reaching refers to transporting the arm and hand to the target object, whereas grasping refers to the precise positioning of the fingers-and-thumb such that one can accurately grip the target object effectively (van-de-Kamp & Zaal, 2007). In a standard kinematic paradigm, the reach component is measured via wrist velocity, with other highly specific dependent measures derived from this, such as movement time (MT), reaction time (RT), and time to peak velocity (TPV) (Hibbard & Bradshaw, 2002). Under standard viewing conditions, the velocity of the wrist typically peaks at ~40% of the total movement duration (Jeannarod, 1981).

The grasping component is measured via the distance between the thumb and index finger (grip aperture) and this has been repeatedly shown to precisely scale with both object size and position in the workspace (e.g. Connolly & Goodale, 1999). Under normal viewing

conditions with visual feedback, maximum grip aperture (MGA) typically occurs ~75% relative to the total movement time (Glover, 2002). Numerous other studies have confirmed Jeannerod's (1984) division of prehension into two distinct and separable components (Dohl, Ostermann, Hefter & Freund, 2000; Shallice, Venable & Rumiati, 2005) with some authors demonstrating that these, furthermore, have distinct neural substrates (e.g. Cavina-Pratesi et al. 2010).

Aim 1: A comparison of open- as compared to closed-loop reaching.

Via the manipulation of visual feedback – either with or without an on-line view of the participants' reaching hand-and-limb - variables in both the reaching and grasping components are affected in various kinematic experiments (e.g. Schettino, Adamovich & Poizner, 2003). With regard to the reaching or transport component, when online visual feedback is prevented (so-called 'open-loop' trials), it has been demonstrated that the movement duration increased and that such reaches had a relatively later onset for peak velocity as compared to trials in which on-line visual feedback was available (so-called 'closed-loop' trials) (Connolly & Goodale, 1999; Chapman & Goodale, 2010).

Yet there exists substantial controversy in the literature with regard to the effect of visual feedback on the grasp component of manual prehension. Whereas certain experiments report significant differences in MGA across open- and closed-loop trials and hypothesised that this is due to a compensatory technique which allows for greater margins of error (Berthier, Clifton, Gullapalli, McCall & Robin, 1996; Westwood, McEachern & Roy, 2001) others have reported no difference between the two viewing conditions when using an adjustable occluding device designed to keep light levels held constant (Connolly and Goodale (1999)).

Although both Berthier et al. (1996) and Connolly and Goodale (1999) reported a temporal delay in the time to maximum grip aperture (TMGA) during open-loop trials, these

authors showed that MGA still occurred at the same percentage of movement time across both types of condition. In other words, the profile shape was maintained but was relatively 'drawn out' or delayed within the temporal (or time) domain.

Aim 2: A comparison of 3D depth cues across open- and closed loop conditions.

In the last 20 years it has become apparent that all items in a visual scene are processed in the same fashion by the brain; certain cues in the visual scene impact prehension movements to a greater extent than others do (Chapman & Goodale, 2010; Howard & Tipper, 1997; Jax & Rosenbaum, 2007). Specifically, various studies have demonstrated that the brain not only identifies and encodes information about the target object, but that the neural architecture also takes into account the presence of non-target objects located within the surrounding area (Rice et al. 2006; Tipper, Howard & Jackson, 1997; Tresilian, 1998). For example, Tipper, et al., (1997) demonstrated that hand trajectories were affected by the presence of non-target objects, even when such non-target objects did not physically obstruct the path of the hand to the target object. When these items were present in the workspace, the trajectory paths of the reaching hand significantly deviated away from the perceived obstruction. Two differing hypotheses have been put forward to explain this phenomenon. The first, known as the 'obstacle avoidance' hypothesis postulates that we unconsciously maintain a minimum distance between themselves and objects during reach-to-grasp movements (Dean & Brüwer, 1994). The second hypothesis puts forward that the non-target objects may act as distractors and therefore interfere with movement planning (Tipper et al. 1997). Recently, Chapman and Goodale (2008) have reported that it is the obstacle avoidance hypothesis that best accounts for empirical data. Nevertheless, the observation that hand trajectories are affected by the presence of non-target objects in the workspace is directly relevant to the present study, in which the presence of non-obstructing 3D depth cues may contribute in a similar fashion to other forms of non-target objects.

Others have investigated the effect such non-target objects have upon reaching movements via a systematic variation of their size and position on the work-surface (Mon-Williams, Tresillian, Coppard & Carson, 2001; Chapman & Goodale, 2008). Although in the Mon-Williams et al. (2001) study, none of the objects interfered physically with the trajectory path taken by the hand when no objects were present, it was reported that certain positions of the non-target object induced the reaching hand to deviate from this path and to achieve a relatively lower peak velocity. Both Mon-Williams et al. (2001) and Chapman and Goodale (2008) reported that objects presented in front of the goal caused the reaching arm to deviate from the non-occluded trajectory path significantly more than objects situated further back in the workspace. In addition, reaches were longer in duration and coupled with a decrease in peak velocity. These data provided additional support to Tipper et al's. (1997) observation that reach paths veered significantly further away from near objects as compared to far objects. Regardless of the depth at which the objects were presented, Chapman and Goodale, (2008) reported that objects situated to the right of the right (reaching) limb caused more deviation than those that were situated to the left of the reaching limb. These same authors hypothesised that "a right-hand reach will be more affected by obstacles on the right side of space, especially toward the end of the reach" (p.95).

Although Mon-Williams et al. (2001) reported that object height did not have a significant impact upon reach-to-grasp movements, this finding has been disputed by Chapman and Goodale (2008). These latter authors reported that the height of an object did affect the trajectory paths, but only when placed slightly in front of the goal. These authors reported that elongated or effectively 'taller' objects caused the hand to deviate further away as compared to shorter objects. Chapman and Goodale (2008) argue that Mon-Williams et al. did not find a similar effect due to the objects not being placed in the so-called 'sensitive location'. This debate is particularly relevant to the present study, owing to the height

differences in 3D Depth Cues needed to create a constant retinal image size when placed at varying distances relative to the observer.

Aim 3: The effect of non-obstructing 3D depth cues on trajectory paths.

Although there has been a considerable amount of research conducted into the effects of visual feedback of the reaching hand-and-limb within the kinematic domain, there is a relative paucity of studies that have examined any possible effect on hand trajectories in the presence of other sources of visual input, for example, non-obstructing 3D non-target objects that are situated within our everyday (or natural) environment. This is surprising, given that other sources of online visual feedback – in addition to visual feedback of the reaching hand and limb as introduced above - are known to influence reach-to-grasp movements. We consequently postulated that objects situated within the participants' peri-personal space might also influence a variety of kinematic measures. Moreover, Chapman and Goodale (2010) sought to address this problem and build upon their own previous work (Chapman & Goodale, 2008). In their experiment, participants executed all reaches in an open-loop environment only. By contrast, in their 2010 study participants executed reaches in a mixture of open- and closed-loop conditions. It was reported that the trajectories of the reaching arm were not significantly affected by visual feedback - movements took the same trajectory path regardless of whether or not participants could see their hand in flight. Additionally, in both visual conditions it was reported that single objects located to the right of the right (reaching) hand induced the greatest deviation in trajectory paths, thus adding support to their 2008 hypothesis. An area of future research that has been suggested by Chapman and Goodale (2008; 2010) was to investigate the effect of meaningful properties of non-target objects - such as cues to depth - on reach-to-grasp movements.

No experiment has yet investigated the effect of tightly retinal-size controlled non-target objects on either kinematic measures (MGA, PV etc.) or trajectory paths while

manipulating visual feedback. The purpose of the present study was therefore to: 1) address the debate in the literature with regard to the effect of visual feedback on MGA; 2) investigate any potential effects of 3D non-target depth cues on reach-to-grasp kinematics of the moving limb across both open- and closed-loop trials; and 3) to investigate the potential effects of non-obstructing non-target 3D depth cues upon the trajectory paths of the reaching hand. Upon rigorously addressing such issues, it is hoped that a greater understanding of manual prehension in more 'naturalistic environments' can be achieved which may enable neural engineers to develop more efficient and effective reach-to-grasp decode algorithms for brain-computer interfaces by determining which outputs – oftentimes arising from primary motor cortex (or M1), need to be compensated for.

In the present report, participants performed reach-to-grasp movements in both open- and closed-loop conditions. During each of the movements, one of three 3D non-target depth cues was placed within the experimental workspace with varying dimensions and location such as to maintain a consistent retinal image size. It was ensured that these depth cues were positioned such that they did not physically interfere with the trajectory path taken by the reaching limb. The present study reports that both visual feedback and the presence of a depth cue had a profound effect on reach-to-grasp movements.

Materials and Methods

Participants

Eight participants were examined in the present study (four female and four male) from Durham University. Participant age ranged from 19 to 41 years (*M*=24.8 years, *SD*=9.5). Participants were tested for handedness and normal stereoscopic vision using the Edinburgh Handedness Inventory (Oldfield, 1971) and the Frisby Stereo Test (Clement Clarke International Ltd, London, UK), respectively. All were determined to be right handed and to possess depth acuity. All participants provided informed consent prior to testing and the experiment herein received ethical approval by the Durham University Department of Psychology Ethics Committee. The present sample size was selected based on previous work by one of the authors of the present study (Connolly & Goodale (1999)), and, critically, this earlier study also compared open- and closed-loop reach-to-grasp kinematics in healthy participants with a particular emphasis placed upon the transport component. Given that the previous study also had 8 participants and that this yielded sufficient statistical power to examine the transport component and to obtain significant differences, we therefore tested the same number of participants in the present experiment, in which trajectory paths (which are also based upon the transport component, or wrist sensor) were examined in detail.

Apparatus

Insert Figure 1 here

Participants were seated in front of a square white workspace that had an area of 3721cm^2. Their heads were stabilised using a non-metallic head-and-chin rest such that their eyes were 50cm above the workspace. The combination of the chin-rest and the fixation point ensured that for all participants, head position remained constant throughout the entire

experiment such that the three different depth cues created the exact same size on the retina (12.2 degrees of visual angle) when positioned at one of the three possible locations. Participants were unable to see their initial hand position, owing to the fact that the start key was located directly below the chin-rest. Three wooden blocks (so-called Efron shapes) were used as the targets for reaching-and-grasping. All of the blocks had the same surface area of 71cm^2 and height of 1.0cm but varied with regard to width and length. The dimensions of each block were as follows: 3.0x8.1cm, 4.1x6.2cm and 5.0x5.1cm.

Participants began each trial with their right index finger and thumb placed upon the start key situated at the head/body midline. One target block was present in each trial and was always situated in-line with the middle depth cue at one of two locations: 30^o to the left or to the right of the start key (Figure 1). Throughout all trials participants were instructed to fixate their gaze upon a stable point that was situated along the midline precisely 61cm from the start key. The fixation point was positioned at the top of a 10cm block. This generated a viewing angle of ~39^o.

One of three possible depth cues was placed in the workspace with varying dimensions and location so as to maintain a constant retinal image (12.2 degrees of visual angle). The 'Front' cue was 6.5x3.0x3.0cm, the 'Middle' cue was 7.2x3.5x3.5cm and the 'Back' cue was 8.1x3.9x3.9cm. All of the depth cues were placed along the midline and at 30.5, 40.5 and 50.5cm relative to the location of the start key.

Three sensors were attached to the participant's right (reaching-and-grasping) hand or wrist using adhesive tape: 1) on the styloid process of the radius; 2) on the right corner of the thumb nail; and 3) on the left corner of the index finger. The leads from the sensors were taped along the arm and torso to ensure each participant was able to move in a natural fashion. Sensors were then tracked using the trakSTAR kinematic system (Ascension

Technologies, Burlington, VT). Liquid Crystal shutter goggles (Plato System, Translucent Technologies Inc.) were worn by participants throughout the experiment and prevented visual feedback during 50% of all trials. The trajectory of the wrist (at 25%, 50% and 75% of the reach duration) was measured using the wrist sensor (situated on the styloid process of the radius).

Procedure

At the outset of each trial, participants were required to touch their right thumb and index finger together and to place them on the start key. In between each trial, the goggles were shut to allow the experimenter to quietly arrange the target block and depth cue for the subsequent and upcoming trial. Once ready, the trial was initiated during which time the goggles opened for precisely two seconds in order to provide visual information to the participant of the full experimental workspace. A beep was then produced which represented the 'go' signal for the participant to reach for the target block as quickly and as accurately as possible. Participants were instructed to reach for the block, grasp it using a standard precision grip (between the index and thumb), lift it slightly off the table, place it back down, and return to the start key.

In the open-loop condition, the shutter goggles closed as soon as the participant's fingers lifted off the start key. This was implemented to prevent visual-based online corrections of movement. In the closed-loop condition, the goggles remained open such that participants were able to make online corrections during their reach-to-grasp movements. Data collection began as soon as participant's movement velocity increased above a predetermined threshold of 50mm/s, as per previous kinematic studies (e.g. Cavina-Pratesi & Hesse, 2013). Throughout the experiment, participants were instructed to maintain their gaze position upon the fixation point at all times during the reach-and-grasp movement (and the

trial was aborted if they did not do so). Although eye tracking equipment was impractical with the shutter goggles and was thus not used, fixation was monitored by both experimenters and participants were instructed throughout to maintain fixation on the fixation point throughout.

During both open- and closed-loop trials participants reached three times (all trials were pseudorandomised) for each of the three target blocks at both of the locations and with one of the three depth cues present for a total of 54 trials (108 across both testing conditions). Counterbalancing was employed to determine which condition participants were presented with first so that 50% started on open-loop and the remaining 50% on closed-loop. Within each condition, the trials were presented in a pseudorandom order. Prior to the onset of both conditions, participants were given five practice trials. If an error occurred during an experimental trial - such as dropping a block or breaking fixation - the trial was discarded and repeated immediately.

Dependent Measures

The wrist sensor provided the following dependent measures: reaction time (RT), total movement time (MT), peak velocity (PV), time to peak velocity (TPV) and the percentage of movement time at which peak velocity occurred (%TPV). Maximum grip aperture (MGA), time to maximum grip aperture (TMGA) and the percentage of movement time at which maximum grip aperture occurred (%TMGA) were calculated from the thumb and finger sensors.

Statistical Analyses

Mean values were calculated for each participant for all Dependent Measures collapsed across the three replications for each possible combination of Block, Block Position

and Depth Cue for the open- and closed-loop conditions. These mean values were then entered into a separate 2x2x3x3 (Viewing Condition x Block Position x Block Dimensions x Depth Cue Position) Repeated Measures Analysis of Variance (ANOVA). Parametric assumptions were met unless otherwise stated. Multiple t-tests were corrected for using a Bonferroni correction. Our idea to employ 3D depth cues was based on previous research by Chapman & Goodale (Chapman & Goodale 2008; Chapman & Goodale 2010). We hypothesized that since LEDs, for example, in their earlier work, influenced reach-to-grasp kinematic trajectories, that more "naturalistic" 3D depth cues could have an even more profound effect on these very same trajectories (and such an experiment was suggeseted as useful future work by these same authors). This framework therefore provided the justification to employ a four-way data structure.

To investigate the trajectory paths of the moving hand during the reaching phase using the wrist sensor, the total movement was divided into three separate proportions: hand location at 25%, 50% and 75% of the total movement time. A second variable, 'Depth Cue Comparison', was calculated and this represented the difference between hand locations throughout the movement with regard to the particular depth cue that was present in the workspace for that trial type. This was calculated by subtracting the hand locations when one depth cue was present from locations when a different depth cue was present: Middle from Front (F-M), Back from Front (F-B), and Back from Middle (M-B). This additional dependent variable provided for the systematic investigation of the relative difference in trajectory path between the depth cues for both locations of the target block. These data were then entered into separate 2x2x3x3 (Viewing Condition x Block Position x Depth Cue Comparison x Reach Proportion) repeated-measures ANOVA. As before, parametric assumptions were met unless otherwise stated and multiple t-tests were corrected for using a Bonferroni correction.

Results

Here it is reported that reach-to-grasp movements significantly differed in Maximum Grip Aperture (MGA), Reaction Time (RT) and Movement Time (MT) across open- as compared to closed-loop conditions. Peak Velocity (PV), Time to Peak Velocity (TPV) and Time to Maximum Grip Aperture (TMGA) were all significantly affected by the presence of 3D Depth Cues. When the target block was located on the left-hand side of the workspace, trajectory paths significantly differed, and this was dependent upon which 3D depth cue was present within the reaching environment. Notably, this substantial effect *was not observed when the target block was located on the right side of the workspace*.

Kinematic Measures

As shown in **Table 1**, MT and RT significantly increased when participants did not have visual feedback of their moving limb as compared to when they did have such feedback [$F_{(1,7)}$=11.238, p=.012, η^2p=.616 and $F_{(1,7)}$=5.786, p=.047, η^2p=.453, respectively]. Despite some evidence to suggest that PV was marginally slower without visual feedback [$F_{(1,7)}$=5.030, p=.060, η^2p=.418] TPV did not significantly differ for open- as compared to closed-loop trials [$F_{(1,7)}$=1.88,8 n.s., η^2p=.212]. Had further subjects been tested, PV would presumably have reached significance as a result of enhanced power (refer to the Methods for our justification of the sample size). With regard to the grasping component of the reach, participant's MGA was significantly greater [$F_{(1,7)}$=19.267, p=.003, η^2p=.734] with further evidence to suggest that the time taken to reach MGA was marginally delayed [$F_{(1,7)}$=4.213, p=.079, η^2p=.376] during open- as compared to closed-loop trials. Nevertheless, the percentage of the MT at which MGA occurred did not significantly differ across the open- and closed-loop conditions [$F_{(1,7)}$<0.0001, n.s., η^2p<.001].

The position of the block significantly affected certain dependent measures. When the block was situated on the contralateral side (or left side) relative to the reaching hand-and-limb, reaches were significantly longer in duration [*M*=944.3ms] as compared to when the block was situated on the ipsilateral side (or the same side as the right reaching limb) [*M*=753.4ms, $F_{(1,7)}$=44.977, p<.001, η^2p=.865]. Position was also found to significantly affect the time at which both PV and MGA occurred. When the block was situated on the contralateral side, PV and MGA both occurred later in the reach-to-grasp profile [*M*=348.5ms and *M*=736.3ms, respectively] - as compared to when the block was situated on the ipsilateral side of the reaching workspace [*M*=298.5ms, $F_{(1,7)}$=56.793, p<.001, η^2p=.890 and *M*=571.7ms, $F_{(1,7)}$=40.444, p<.001, η^2p=.852 respectively]. Block position did not affect any other dependent measures.

Figure 2 presents the mean MGA for each block in both the open- and closed-loop conditions. There was a significant difference in MGA for the different blocks. Specifically, relatively 'wider' blocks induced a larger distance between the index finger and the thumb [$F_{(2,14)}$=35.523, p<.001, η^2p=.835]. Furthermore, there was a significant difference in both the absolute time and percentage of movement time at which MGA occurred [$F_{(2,14)}$=3.974, p=.043, η^2p=.362 and $F_{(2,14)}$=6.891, p=.008 ,η^2p=.496 respectively]. An inspection of cell means revealed that as the block width increased, the time at which MGA occurred was relatively later on during the reach-to-grasp - both as a percentage of the total reach duration and in a simple absolute fashion. Notably, the block widths did not affect any other dependent measures.

Insert Figure 2 here.

As shown in **Table 2**, both PV and TPV significantly differed across the three depth cue distances [$F_{(2,14)}$=11.116, p=.001, η^2p=.614 and $F_{(2,14)}$=13.742, p<.001, η^2p=.663,

respectively]. An inspection of cell means showed that as depth cues progressively moved further towards the back of the workspace, PV progressively increased. This is a highly notable finding, owing to the fact that there was no condition in which the depth cue actually 'blocked' the path of the hand to the target block. Analysis of post-hoc tests revealed that although the time at which PV occurred during the reach did not significantly vary between the middle and back-situated depth cues, it was significantly delayed for the front depth cue. The time taken to reach MGA was significantly affected by the depth cues [$F_{(2,14)}$=10.383,p=.002, η^2p=.597]. As the depth cue was positioned further toward the back of the workspace, MGA occurred earlier in the reach-to-grasp movement.

Kinematic Interactions

Figure 3 shows the interaction involving Condition x Depth cue effect on MGA [$F_{(2,14)}$=4.574, p=.030, η^2p=.395]. Three paired-samples t-tests revealed that MGA significantly increased for open- as compared to the closed-loop condition and for all 3 depth cues [Front t(7)=3.365, p=*.012;* Middle t(7)=4.517, p=*.003;* Back t(7)=4.621, p=*.002*]. However, additional paired-samples t-tests indicated that MGA did not significantly vary between depth cues for either open- or closed-loop trials. Figure 4 shows a second interaction involving Position x Depth Cue effect on TMGA [$F_{(2,14)}$=7.156, p=.007, η^2p=.505].

Insert Figure 3 here.

Three paired-samples t-tests revealed that MGA occurred significantly earlier for all depth cues when the target block was located on the right side of the workspace [Front t(7)=6.514, p<0.001; Middle t(7)=6.495, p<.001; Back t(7)=5.381 p=.001]. Further paired-samples t-tests showed that when the target block was located on the left side of the workspace, MGA occurred significantly later in the presence of the Front depth cue compared to both the Middle [t(7)=4.160, p=.004] and Back depth cue [t(7)=3.149, p=.016].

When the target block was placed on the right side of the workspace, MGA was significantly delayed in the presence of the Front Depth Cue as compared to the Back Depth Cue [$t(7)=2.489$, $p<.042$] yet there was no significant difference for when MGA occurred across the Front and Middle situated Depth Cues [$t(7)=0.882$, n.s].

Insert Figure 4 here.

A four-way interaction involving Condition x Position x Depth Cue x Block for MGA was found [$F_{(4,28)}=2.726$, $p=.049$, $\eta^2p=.280$]. Unfortunately, this interaction – when probed with further t-tests - was not interpretable.

In addition to the significant interactions already discussed, the analysis highlighted some evidence for two further interactions. The first such interaction was a Depth Cue x Block on PV [$F_{(4,28)}=2.626$, $p=.056$, $\eta^2p=.273$]. The second marginal interaction was a Condition x Depth Cue x Block on time to MGA [$F_{(4,28)}=2.239$, $p=.090$, $\eta^2p=.242$]. Owing to their marginality, neither interaction was investigated further as no significant effects would have presumably been found after the application of the conservative Bonferroni correction. Had additional participants been tested, it would have been likely that these both would have reached significance owing to their reasonably large effect sizes (refer to **Methods** for a justification of our sample size).

Trajectory Analysis

Figure 5 illustrates the trajectory paths taken by a representative participant when visual feedback was prevented (open-loop) for the various combinations of depth cue and target block position. As can be seen, when the target block was located on the left side of the workspace hand trajectories differed depending on the depth cue present. However, when the

target block was located on the right, trajectories taken by the moving hand remained similar across all three of the depth cues.

Insert Figure 5 here.

Figure 6 presents the difference in trajectory paths of the reaching hand-and-limb as a function of Depth Cue Comparison, Block Position and Visual Feedback at 25%, 50% and 75% of the movement trajectory. Although it was found that there was no significant effect of Visual Feedback upon the trajectory path disparities [$F_{(1,7)}$=0.053, n.s, η^2p=.007] there was a significant effect of Block Position [$F_{(1,7)}$=31.506, p=.001, η^2p=.818]. Post-hoc tests revealed that the trajectory paths taken by the reaching arm were affected significantly to a greater degree by the depth cues when the block was positioned on the left side of the workspace (M=29.790mm) as compared to when the block was positioned on the right (M=1.96mm, p=.001).

Insert Figure 6 here.

To further investigate the effect of Block Position (left or right) upon the trajectory paths, data was entered in to a 2x3x3 (Visual Feedback x Depth Cue Comparison x Reach Proportion) repeated measured ANOVA. When the target block was located on the right side of the workspace it was found that there was a significant main effect of Depth Cue Comparison [$F_{(2,14)}$=5.967, p=.014, η^2p=.456]. Nevertheless, when probed with both post-hoc tests and paired-samples t-tests it was found that the difference in hand location did not significantly vary across the three depth cues comparisons. Notably, there were no other significant main effects or interactions.

In contrast, when the target block was located on the left side of the workspace there were two significant main effects. The first effect was for the Depth Cue Comparison

[$F_{(2,14)}$=16.976, p<.001, η^2p=.708]. Post-hoc tests indicated that disparities in trajectory path were significantly greater between the F-B comparison (M=44.69mm), as compared to the F-M (M= 33.04mm, p=.013) and M-B comparisons (M=11.64, p=.006). Additionally, the disparity in trajectory path between F-M was significantly greater than the disparity between M-B (p=.044). The second effect was on Reach Proportion [$F_{(2,14)}$=15.865, p<.001, η^2p=.694]. Post-hoc tests indicated that the disparity in hand position was significantly different for all three proportions of the reach that were examined. Hand positions were most similar at 25% of the movement (M=20.79mm) with differences increasing at both 50% (M=31.36mm) and 75% (M=37.23mm). Similar to what was reported when the block was located on the right-hand side of space, there was no significant effect of Visual Feedback [$F_{(1,7)}$=0.193, n.s., η^2p=.027].

Trajectory Interactions

In addition to the main effects found when the block was located on the right side of the workspace, there was a 'Depth Cue Disparity x 'Reach Proportion' interaction on trajectory path disparity as presented in Figure 7 [$F_{(4,28)}$=8.670, p<.001, η^2p=.553]. Paired-samples t-tests were conducted to examine the difference in trajectory disparity between the three comparisons (F-M, F-B and M-B) for all three proportions of movement.

Insert Figure 7 here.

It was found that at 25% of the reaching movement, disparity between trajectory paths was significantly larger for F-B compared to both M-B and F-M [t(7)=4.970, p=.002 and t(7)=4.611, p=.002 respectively]. This pattern was also true of reaches at 50% of the movement with disparity between trajectory paths significantly larger for F-B compared to both M-B and F-M [t(7)=4.693, p=.002 and t(7)=4.200, p=.004 respectively]. However, at 75% of the reaching movement, the only disparity to remain significantly different from the

others was between F-B which was larger than that of M-B [$t(7)=4.723$, $p=.002$]. After the application of the Bonferroni correction, the disparities between M-B and F-M did not significantly differ at any proportion of the movement.

Further paired-samples t-tests were conducted to examine the difference in trajectory disparity within each comparison across the three proportions of movement time. After the Bonferroni correction was applied, the only significant differences in trajectory disparities that remained were for F-B between both 25%-50% and 25%-75% [$t(7)=-4.122$, $p=.004$ and $t(7)=-4.044$, $p=.005$ respectively]. As the movement progressed, disparity in trajectory paths became significantly increased. For all other comparisons, disparities in trajectory paths did not significantly vary across the examined movement proportions.

Discussion

The present study had three primary aims: 1) to address the debate in the literature with regard to the effect visual feedback has on MGA; 2) to investigate any potential effects 3D non-target depth cues may have on reach-to-grasp kinematics of the reaching limb during both open- and closed-loop trials; and 3) to investigate the effects (if any) non-obstructing non-target 3D depth cues had upon the trajectory paths of the reaching hand and limb. Upon addressing these three aims, it is hoped that a greater understanding of manual prehension can be achieved which could assist neural engineers to develop more efficient and effective reach-to-grasp decode algorithms for brain-computer interfaces (or so-called 'compensatory algorithms').

In addition to replicating previous findings, this experiment extends the literature with regard to the effect 3D depth cues – akin to those in our natural everyday environment - have on reach-to-grasp movements. Similar to visual feedback, it was found that depth cues affected both the reaching and grasping component of the movement. As the depth cues progressively moved forwards in the workspace (towards the start-key), reach-to-grasp movements were characterised by significantly reduced peak velocities, coupled with a later onset of both peak velocity and maximum grip aperture; reaches made in the presence of the front depth cue had the lowest peak velocity, and took the longest time period to reach both PV and MGA. Additionally, the present study reports an interaction between the depth cue present and position of the target block for time to MGA; MGA occurred earliest when the target block was located on the right side of space (i.e. depth cue to the left of the reaching arm) and when the back depth cue was present. These findings are generally consistent with Mon-Williams et al. (2001) and Chapman and Goodale (2008) – as both studies reported that non-target objects had the greatest impact on kinematic measures, such as peak velocity and total movement duration, when positioned nearer in depth and to the right of the target block.

Despite the fact that both Mon-Williams et al. (2001) and Chapman and Goodale (2008) reported that the reduction in peak velocity led to a significant increase in overall movement time when non-target objects were situated closer in depth as opposed to when they were further back in the workspace, this was not found in the present study. It can be argued that this may be a result of the additional depth-cuing properties of the non-target objects. It may be the case that despite not achieving such high peak velocities, by providing additional visual information about the scene, the reaching hand-and-limb was capable of move more efficiently than in both previous studies in which the non-target objects did not cue depth. Although this idea cannot be conclusively validated from the current data, future research (as discussed below) may provide for greater insight here.

The final aim of this study was to investigate the effect of non-obstructing non-target 3D depth cues upon the trajectory paths of the reaching hand. Here it is reported that when reaches were made to the ipsilateral (right) side of the workspace, trajectory paths did not significantly vary at the three proportions of the reach examined depending on which depth cue was present. In contrast, when reaches were made to the contralateral (left) side of the workspace, large deviations in trajectory path were observed depending on the depth cue present - as the depth cue moved progressively back in the workspace, the reaching hand-and-limb took a more direct, 'efficient', route to the target block. Additionally, these deviations significantly increased as the movement progressed. Interestingly, visual feedback did not have a significant effect upon trajectories. Because neither Chapman and Goodale (2010) nor the present study found a significant effect of visual feedback upon trajectories, it is suggested that online visual feedback is not essential to conduct accurate reach-to-grasp movements. Instead the present data highlights the proficiency of the neural architecture at preparing and executing ballistic movements. Furthermore, we believe that the findings therefore support the obstacle avoidance hypothesis as put forward by Dean & Bruwer (1994)

and supported by Chapman and Goodale (2008) rather than the distractor hypothesis (Tipper et al. 1997), given that we observed that the depth cue that was 'out of reach' or situated beyond the particpants' peri-personal space had a relatively reduced impact on reach trajectories.

The results of the present study both support and extend the data reported by Chapman and Goodale (2010). The similar pattern of trajectory paths taken between these two studies is highly notable given the additional experimental controls employed by the present study. Whereas Chapman and Goodale (2010) did not control for either the retinal size of the non-target objects or participant gaze fixation, both of which could have acted as confounds, the present study did so cogently. Additionally, the present study used a real, graspable 3D object as a target for reach-to-grasp movements as opposed to an LED light. Nevertheless – and despite such methodology differences - the similarities of findings between the two studies supports Chapman and Goodale's (2010) results and also provides support for the idea that their data cannot be explained due to methodological confounds. Additionally, the present study reinforces Chapman and Goodale's (2010) hypothesis that objects located to the right of the right (reaching) hand will have the greatest effect upon the trajectory path taken, and that this deviation is especially noticeable towards the end of the reach.

Although Chapman and Goodale (2010) did not provide a mechanism for these observed effects (specifically that trajectory deviations were greatest for non-target objects located closest in depth and were reduced the further back in the workspace the objects were moved, and, that reaches to the left were affected to a greater degree than those to the right) the present discussion seeks to offer a working hypothesis. It may be the case that the activity of neurons within the parietal cortex were responsible for the effect depth cue position had upon the trajectory path of the reaching hand-and-limb. Holmes and Spence (2004) have

reported that neurones in the parietal cortex code for an area of space referred to as 'peripersonal space'. This 'peripersonal space' is an area that can be acted upon by an individual (such as making a reach-to-grasp movement) without moving their body closer to that same area. It is suggested that because the back depth cue was 'out of reach', and therefore not encoded in the peripersonal space, it had a relatively reduced effect on reach trajectories as compared to the front or middle cues. Similarly, because the middle cue was further away from participants than the front cue, it too may have produced a comparatively weaker effect.

To explain the greater impact the depth cuing non-target objects had upon reaches made to the left side of the workspace, as compared to the right, a second working hypothesis is suggested which relates to the biomechanical relationship between the body and arm. Owing to the fact that reaches made to the right of the workspace did not have to move across the body, whereas movements to the left were, it has been suggested that these two movements are coded for via distinct neuronal ensembles within primary motor cortex, as well as other regions within parietal cortex (Kertzman, Schwarz, Zeffiro & Hallett, 1997). Such a division is argued to exist based upon other behavioural experiments which have reported that movements made to targets on the ipsilateral side of the body as the reaching hand typically show kinematic advantages (e.g. higher PV, lower MT) as compared to those made to the contralateral side (Carey, Hargreaves & Goodale, 1996). Therefore, it may be the case that these separate neural regions, and their relevant inputs, are affected to a different degree by the presence of non-target objects, and potentially cues to depth, and as such produce differing patterns of kinematic data and trajectory paths.

Although the present study extended the methodologies of previous studies and still found similar results, to optimally examine if providing cues to depth has an enhancing effect upon manual prehension, a follow-up study needs to be conducted which would address

certain issues. Although throughout the experiment participants were instructed to maintain their gaze fixation upon a landmark, eye-tracking equipment was not employed – as this was impractical with the shutter goggles - and instead was only monitored by both experimenters. Despite the fact that every effort was made to ensure gaze fixation remained constant throughout, without using eye-tracking equipment it is impossible to state with certainty that this did, in fact, occur. A second methodological inclusion that should be made is the addition of an extra control condition. To be able to investigate if cuing depth has any additional effects upon reach-to-grasp movements beyond other non-target objects, participants should be presented with a differing set of non-target objects in a block of trials. This second set of objects should all be of the same dimensions (i.e. provide differing retinal images) and be positioned in identical locations in the workspace as the depth cues. Upon a comparison of the data from reach-to-grasp movements in the presence of this second set of objects to the data from movements when the depth cues were present, it would be possible to discover the additional impact depth cues may have – and if there were any differences between these two conditions then it can then be argued that it was due to the additional depth cuing properties of the non-target objects.

The findings from the present study, combined with previous literature (Mon-Williams et al., 2001; Chapman & Goodale, 2010) have direct, practical implications for those working on developing reach-to-grasp decode algorithms for brain-computer/machine interfaces. In the last 10 years in particular, profound advancements have been made in the brain-computer/machine interface field such that primates, healthy humans, and even humans suffering from paralysis are able to make reach-to-grasp movements using a neural prosthetic limb prosthesis (Carmena et al. 2003; Nair 2013; Bensmaia & Miller 2014). Upon taking into account the present findings, the computational brain-to-computer decode algorithms employed by these devices to decode neural signals can (and should) be improved.

Specifically, it has been repeatedly shown that both maximum velocity and trajectory path taken are dramatically altered or made 'inefficient' when objects were present in the workspace located to the right of the reaching limb, and that this effect is further modulated by object depth. Therefore, if these deviations were to be factored into the computation of brain-computer interface decode algorithms, it is posited that both the efficiency and accuracy of these algorithms could factor in this 'error' such that the prosthetic arm and hand always takes the most direct route with the prosthesis. Such compensation for motor error would provide paralysed individuals with the most efficient routes for the control of the prosthesis, particularly when situated in a cluttered or 'natural' environment and may even lead to 'performance enhancement' of potential brain machine interfaces that could be used in healthy individuals.

The data from the present study suggest that manual prehension relies on a highly sophisticated neural architecture that takes into account a wide range of visual information. In contrast to previous literature in which depth cues were not provided, the present data demonstrate that the presence of a depth cue has a clear effect on both the kinematics and trajectory path taken of the reaching hand-and-limb during reach-to-grasp movements.

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Figure Legends

Figure 1. The experimental workspace. Each participant's eye remained fixated on the fixation point (FP) and the index finger and thumb rested on the start key (SK). Both a left side (or contralateral) block is shown and also a right side ipsilateral block (although only one or the other was presented on each trial). The three depth cue locations are shown simultaneously (although only one was presented on each trial, Front (F), Middle (M) and Back (B). Critically, the depth cues did not obstruct the reach path to the goal object.

Figure 2. Mean Maximum Grip Aperture (MGA) as a function of Block (1,2,3) x Condition. It is clear from this Figure that MGA scales linearly with block width. In other words, Block 1 had the narrowest width and Block 3 had the widest (with Block 2 in between the two). Second, participants scaled their grip aperture such that this was greater for Open- as compared to Closed-Loop reaches.

Figure 3. Mean Maximum Aperture (MGA) as a function of Condition x Depth Cue. MGA significantly increased for open- as compared to the closed-loop condition and for all 3 depth cues. However, additional paired-samples t-tests indicated that MGA did not significantly vary between depth cues for either open- or closed-loop trials.

Figure 4. Mean Time to Maximum Grip Aperture (TMGA) as a function of Position x Depth Cue. There was a second interaction involving Position x Depth Cue effect on TMGA. Three paired-samples t-tests revealed that MGA occurred significantly earlier for all depth cues when the target block was located on the right side of the workspace

Figure 5. Trajectory of the reaching hand as a function of Block Position and Depth Cue present for a representative participant. n.b. Data presented does not include values past 75% of the movement. Figure 5 illustrates the trajectory paths taken by a representative participant when visual feedback was prevented (open-loop) for the various combinations of depth cue and target block position. As shown here, when the target block was located on the

left side of the workspace hand trajectories differed depending on the depth cue present. However, when the target block was located on the right, trajectories taken by the moving hand remained similar across all three of the depth cues. This supports the idea the brain-machine interface algorithms should incorporate 'motor error' estimations for reaches made to the right of the goal object.

Figure 6: Disparities in trajectory paths at 25%, 50% and 75% of the movement as a function of depth cue comparison, target block position and visual feedback. n.b negative values indicate deviance of the hand towards the right side. Positive values indicate deviance towards the left. Shown is the difference in trajectory paths of the reaching hand-and-limb as a function of Depth Cue Comparison, Block Position and Visual Feedback at 25%, 50% and 75% of the movement trajectory. Although we report that there was no significant effect of Visual Feedback upon the trajectory path disparities, there was a significant effect of Block Position. Post-hoc tests revealed that the trajectory paths taken by the reaching arm were affected significantly to a greater degree by the depth cues when the block was positioned on the left side of the workspace as compared to when the block was positioned on the right.

Figure 7. Mean disparity of hand location as a function of Depth Cue Comparison and Reach Proportion. In addition to the main effects found when the block was located on the right side of the workspace, there was a 'Depth Cue Disparity x 'Reach Proportion' interaction on trajectory path disparity. Paired-samples t-tests were conducted to examine the difference in trajectory disparity between the three comparisons (F-M, F-B and M-B) for all three proportions of movement. It was found that at 25% of the reaching movement, disparity between trajectory paths was significantly larger for F-B compared to both M-B and F-M. This pattern was also true of reaches at 50% of the movement with disparity between trajectory paths significantly larger for F-B compared to both M-B and F-M. However at

75% of the reaching movement, the only disparity to remain significantly different from the others was between F-B which was larger than that of M-B.

Table 1

Effect of visual feedback on reach kinematics. Values = mean (±standard error of the mean)

	Visual feedback condition	
	Closed-Loop	Open-Loop
Movement Time (ms) *	820.5 (40.00)	877.7 (37.44)
Reaction Time (ms) *	531.9 (55.20)	576.4 (49.50)
Peak Velocity (mm/s)	959.3 (76.61)	914.1 (74.63)
Time to Peak Velocity (ms)	314.0 (18.70)	333.0 (21.60)
%Time to Peak Velocity	39.0 (1.10)	38.7 (1.50)
Maximum Grip Aperture (mm) **	95.6 (0.66)	101.5 (1.48)
Time to Maximum Grip Aperture (ms)	632.3 (48.38)	675.0 (57.97)
% Time to Maximum Grip Aperture	77.4 (2.90)	77.3 (4.00)

*p<0.05, **p<0.01, ***p<0.001

Table 2

Effect of Depth Cues on reach kinematics. Values = mean (±standard error of the mean)

	Depth Cue		
	Front	Middle	Back
Movement Time (ms)	862.4 (37.40)	842.9(37.38)	842.0 (43.06
Reaction Time (ms)	554.6 (50.98)	551.4 (54.01)	556.5 (50.15
Peak Velocity (mm/s) **	925.0 (73.35)	935.5 (74.33)	949.6(77.25
Time to Peak Velocity (ms) ***	332.4 (19.32)	318.5(18.40)	319.7 (19.34
%Time to Peak Velocity	39.1 (1.00)	38.5 (1.40)	39.0 (1.30)
Maximum Grip Aperture (mm)	98.4 (1.02)	98.6 (1.12)	98.6 (0.98)
Time to Maximum Grip Aperture (ms) **	675.1 (52.48)	645.8 (50.05)	640.0 (55.08
% Time to Maximum Grip Aperture	78.2 (3.50)	77.2 (3.50)	76.6 (3.30)

*p<0.05, **p<0.01, ***p<0.001

Figure 1.

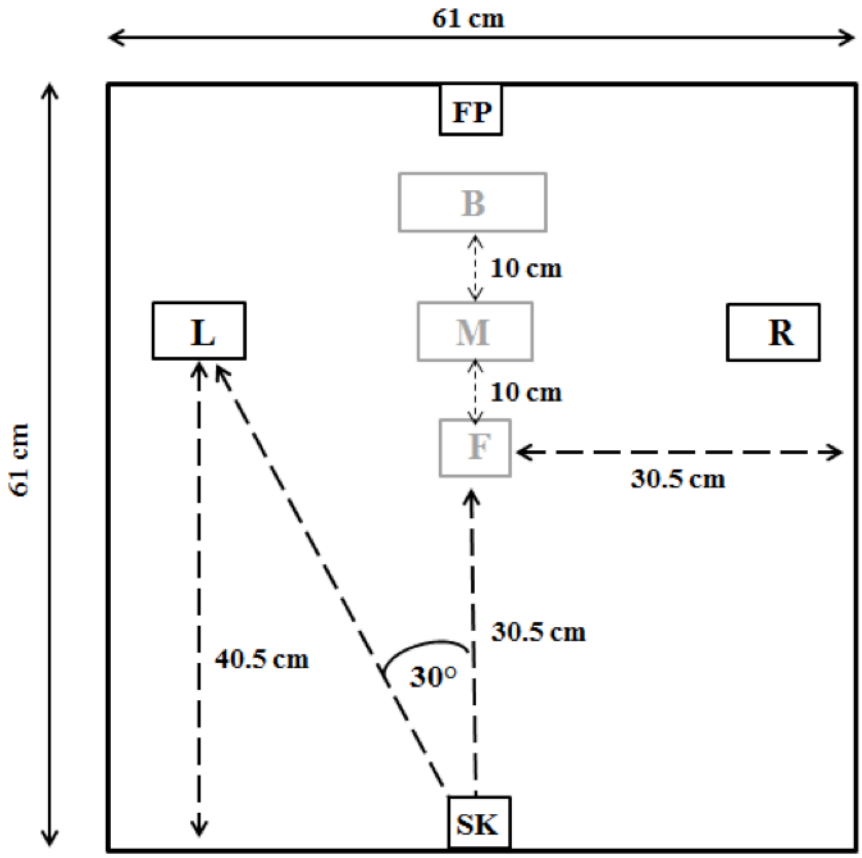


Figure 2.

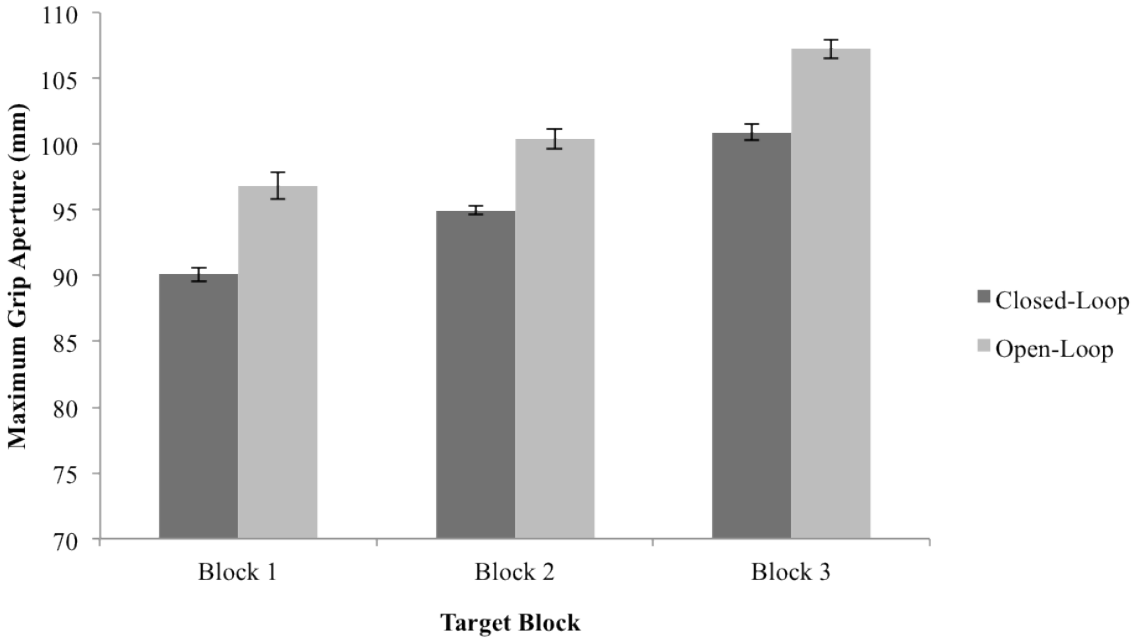

110
105
100
95
90
85
80
75
70
Maximum Grip Aperture (mm)
Block 1
Block 2
Block 3
Target Block
Closed-Loop
Open-Loop

Figure 3.

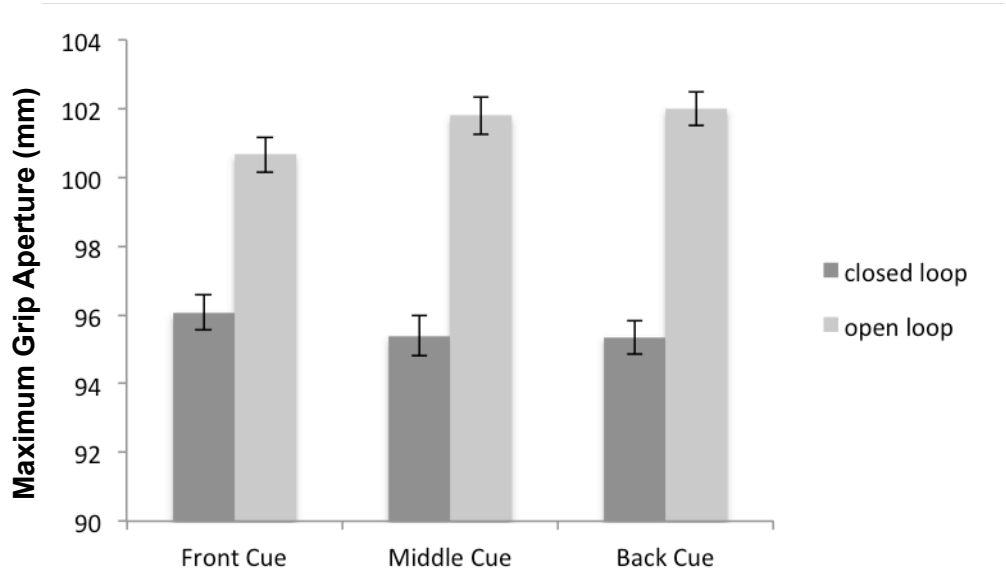

Maximum Grip Aperture (mm)
104
102
100
98
96
94
92
90
Front Cue
Middle Cue
Back Cue
closed loop
open loop

Figure 4.

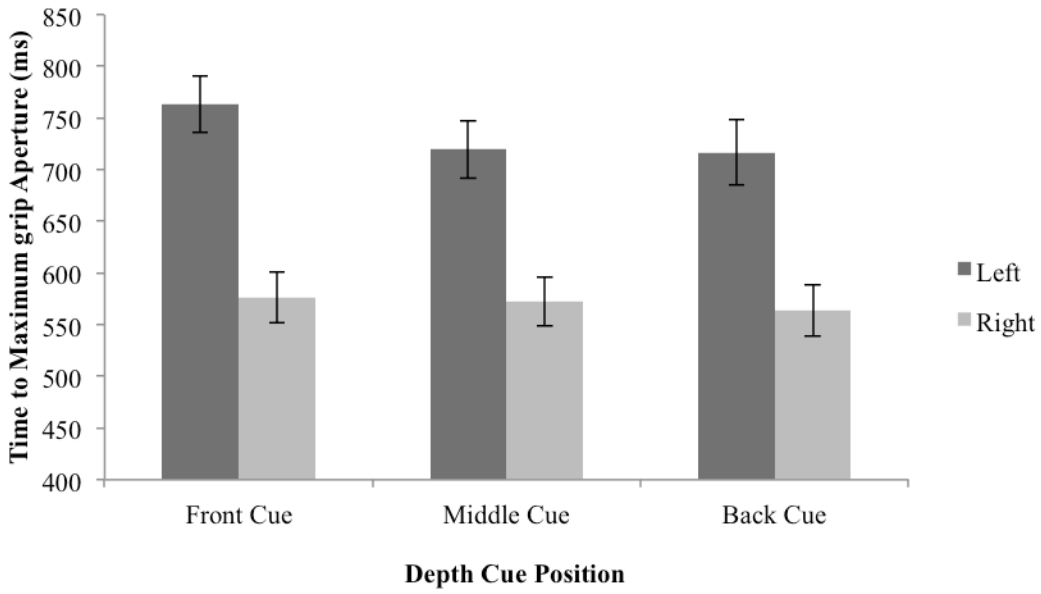

Time to Maximum grip Aperture (ms)
850
800
750
700
650
600
550
500
450
400
Front Cue
Middle Cue
Back Cue
Depth Cue Position
Left
Right

Figure 5.

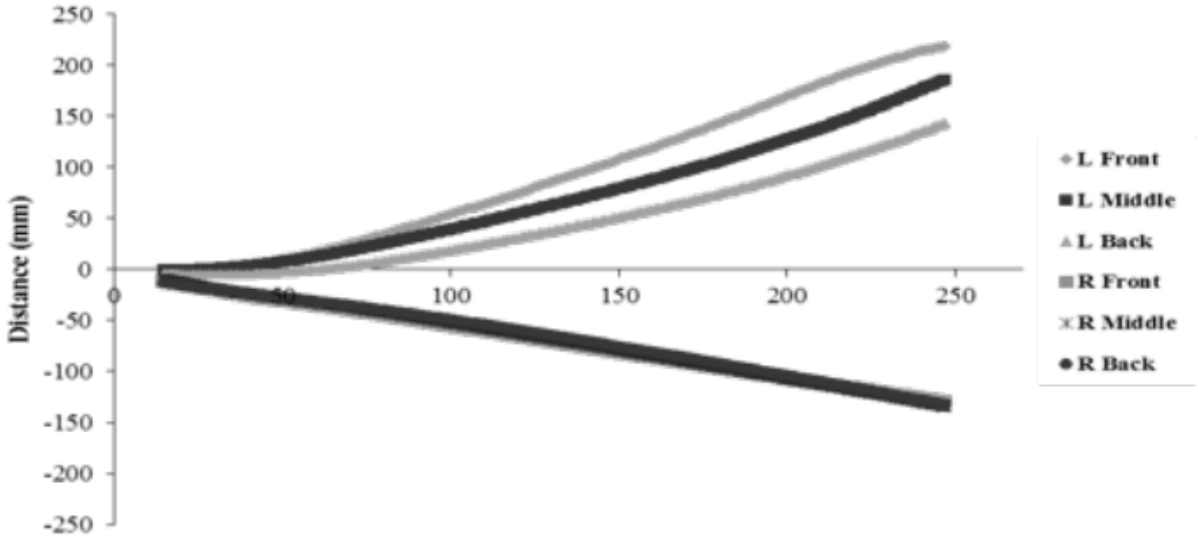

250
200
150
100
50
0
-50
-100
-150
-200
-250
Distance (mm)
0
100
150
200
250
L Front
L Middle
L Back
R Front
R Middle
R Back

Figure 6.

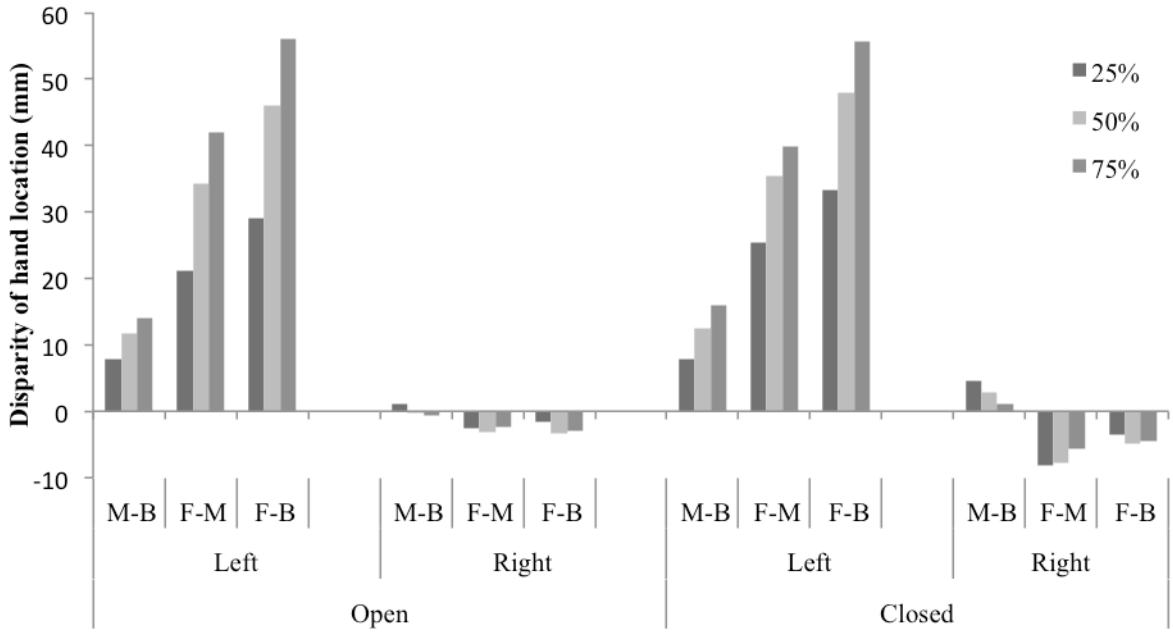
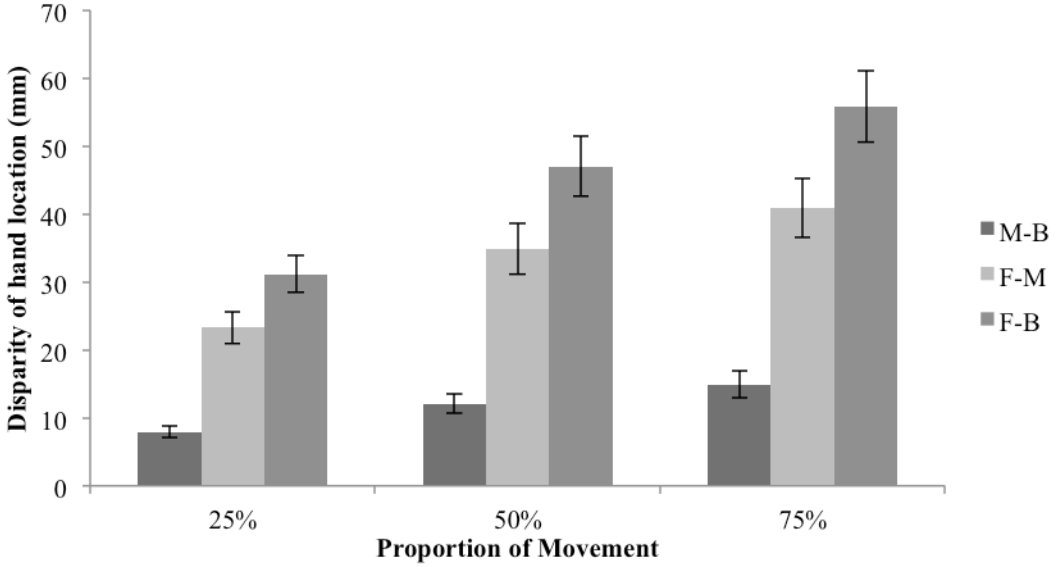

Disparity of hand location (mm)
60
50
40
30
20
10
0
-10
25%
50%
75%
M-B
F-M
F-B
M-B
F-M
F-B
M-B
F-M
F-B
M-B
F-M
F-B
Left
Right
Left
Right
Open
Closed

Figure 7.


70
60
50
40
30
20
10
0
Disparity of hand location (mm)
25%
50%
75%
Proportion of Movement
M-B
F-M
F-B